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CHARACTERISTICS OF THE "BOAT" INDUCTOR
FOR KEEPING LIQUID METAL IN THE SUS-
PENDED STATE

A.A. Fogel', T.A. Siforova and M.M. Mezdrogina

Translation of "Kharakteristiki induktora 'Lod-
ochka' uderzhivayushchego zhidkiy metall vo vzveshe-
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16. Abstract Characteristics of the "boat" inductor for keeping liquid metal in the suspended state are examined. Behavioral features of the liquid metal, and the suspension boundary of liquid metal in the lower position are discussed. It is concluded that the inductor can be used to crystallize metals in the suspended state.			
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CHARACTERISTICS OF THE "BOAT" INDUCTOR
FOR KEEPING LIQUID METAL IN THE SUSPENDED STATE

A. A. Fogel', T. A. Sidorova and M. M. Mezdrogina

When the method is used of melting metals, which before and after melting are kept in the suspended state by an electromagnetic field, the optimal correlations should be maintained between the physical properties of the metal and the main field parameters: frequency and configuration, depending on the design of the inductor used [1, 2].

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Studies conducted by the laboratory of high-frequency electrothermics of the A. F. Ioffe Physico-Technical Institute of the USSR Academy of Sciences, allowed us to pinpoint the characteristics of the inductors that are the most convenient to use. This publication examines the "lodočka**" inductor. This type of inductor was designed in the laboratory in an attempt to create an inductor with an equipotential bottom to allow heating of the metal to begin at the lowest desired power, that is still not sufficient to bring it to the suspended state. This is required when the metal is degasified before it is melted. After being used for the first time in domestic practice [3, 4], this inductor attracted foreign interest.¹ The characteristics of the boat inductor differ significantly from the characteristics of the inductors with reverse loop, while the inductor itself is very important, for example, for researchers who are forced to keep a molten metal in the suspended state for a long time, at an assigned temperature, in a vacuum, where the metal weight changes because of evaporation

*Numbers in right margin indicate pagination in the original text.

**Translator's note: "lodočka" = boat.

¹French patent 1416536, kl. H05, application 24.09.1964, Published 27.09.1965.

during the work.

The boat inductor in its modern design (fig. 1) is two slotted loops, bent upwards on the edges and connected in parallel to a common current supply [4]. Both loops are arranged on the sides of the metal suspended in their field. The inductor is designed to operate with the lowest possible voltage which ensures the absence of electrical discharges when the melting is done in a vacuum. In the initial design of the inductor, the lower parts of the two loops that passed under the heated metal were united into one conductor; the lower conductor was subsequently divided into two parts, and an opening was made between them for passage of the molten metal into the ingot mold.

During the melting, one can only regulate the voltage that is applied to the inductor. The field frequency, and the more so, the shape of the inductor which assigns the field configuration, must be selected in advance, therefore it is quite necessary to know the characteristics of the inductor.

Behavioral features of the liquid metal. A drop of liquid metal that is kept in the suspended state by an electromagnetic field adopts a shape that approximately repeats the shape of the potential depression in the inductor field, and therefore usually differs in shape from the solid metal blank prepared for melting. However, the behavior of the liquid drop in the field has certain features in common with the behavior of a solid metal. This allows us to use a formula that links the power supplied to the metal and the weight of the metal, its physical properties and the field parameters [1]:

$$F = \frac{1}{2} \sqrt{\frac{\mu_0}{\pi \rho f}} A P_s S \quad (1)$$

where F--electromagnetic force that acts on the metal and is equal to the weight of the metal, h; ρ --specific electrical resistance of the metal, ohm; f--field frequency, Hz; μ_0 --magnetic constant;

P_s --power emitted by a unit of metal surface, W/m^2 ; S --surface area of metal, m^2 ; A --dimensionless coefficient which depends on the field configuration at the metal surface.

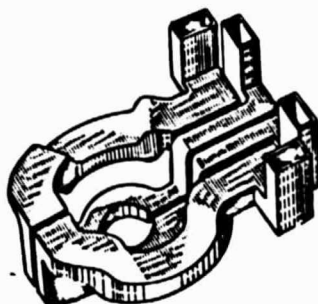


Figure 1. "Boat" Inductor

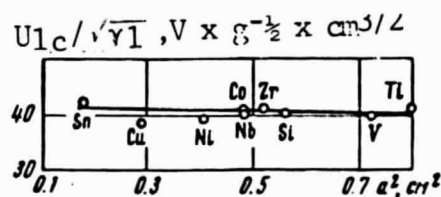


Figure 2. Dependence of the $U_{1k}/\sqrt{\gamma_1}$ Ratio on the Square of the Capillary Constant; Field frequency is 440 kHz

But there is a significant difference in addition to the common features. The minimum frequency of the electromagnetic field that is capable of holding the liquid metal, f_{min} , can be higher than the frequency of the field holding the same metal in a solid state [1]:

$$f_{min} = \frac{\rho h^2}{\pi \mu_0 a^4} \quad (2)$$

where a --capillary constant of the given metal, m; h --height of the column of liquid metal, m.

In weakened field areas, in so-called "holes," the effect of the field on the metal is essentially missing, and the liquid metal does not flow out of the inductor merely because of the Laplace pressure. In order for the Laplace pressure to counterbalance the hydrostatic pressure of the liquid metal column, the metal surface must be convex with a fairly small curvature radius. In this case, the role of the field is reduced to creating the necessary shape of the liquid metal. The field is not capable of forming the metal shape in the necessary way for two main reasons: 1) the frequency of the electromagnetic field is lower than the minimum computed from formula (2); 2) the unsuitable configuration of the electromagnetic field, i.e., the dimensions of the hole are too large, and the convex surface of part of the metal which penetrates into the zone of the weakened field has a greater radius curvature than is necessary to counterbalance the hydrostatic pressure by the Laplace pressure. This field can hold the solid metal, but not hold the liquid metal in the suspended state.

Observing the process of the metal coming out of the inductor, one can see that with a gradual reduction in voltage on the inductor, the drop of liquid metal descends, and after it reaches a certain critical level, the metal begins to flow out. The drop does not fall entirely, as occurred with complete disengagement of the inductor power. The metal, without touching the inductor conductors, flows out in a fairly thin stream and fills the ingot mold.

Controllable output of metal, as it were through a funnel from the field, is based on the possible increase in the size of the hole in the field, with simultaneous preservation of the field intensity, sufficient to hold the main part of the drop of liquid

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metal, equivalent, in the sense of maintaining it in a suspended state, to a piece of solid metal.

Thus, in the lower zone of the inductor into which the metal descends with low voltage on the inductor, it is mandatory that there be a region where the solid metal is suspended, while the liquid flows out. With an increase in metal voltage, rising, the metal falls into a region where it is suspended stably both in the liquid state, and in the solid. A further increase in voltage causes movement of the metal into the upper zone, where the metal is again unstably suspended.

As the metal is moved, falling from the field of one configuration into the field of another configuration, it changes its shape. Observing the shape of the drop of molten metal, suspended in the field of the boat inductor, one can see that the drop has the shape of a kidney bean or half-moon. The bent ends of the drop are directed downwards and are located at the sites of the weakened field in the center of the lateral slotted loops of the inductor. The concavity or extended "belly" of the drop is located under the lower conductors of the inductor, between which there is an outlet opening. The "belly" of the drop hangs down in a direction towards the outlet opening, while the lateral horns of the "half-moon" are pulled inside of the drop.

Suspension boundary of liquid metal in the lower position.
When the drop is lowered in the inductor through a reduction in the voltage applied to it, the metal begins to flow out of the inductor field at the moment it passes a certain critical level. Below this level, the belly of the metal is not held by an electromagnetic field. At the same time, the radius of curvature of the belly is not small enough for the Laplace pressure to counterbalance the pressure of the metal column with the values of the capillary constant of different metals that are encountered in practice. All the metals, therefore, begin to flow out of the

inductor when the drop descends to the same level, defined by the correlation

$$\frac{U}{\sqrt{\gamma} f} = C \quad (3)$$

where U --voltage on the inductor, γ --density of the metal, C --constant magnitude.

Therefore, flowing of all metals from the boat inductor occurs at a voltage that we call the first critical

$$U_{1c} = C \sqrt{\gamma_l} f \quad (4)$$

where γ_l --density of the liquid metal.

Figure 2 presents experimental data which confirm that the outflowing of different metals is subordinate to condition (3), regardless of their physical properties. Experience shows that it also does not depend on the volume of the metal. However, metal with volume less than 2 cm^3 , with voltage close to the critical, is unstably suspended, oscillates, and as a result of vertical swinging can enter the field where the liquid metal is unstably suspended. The minimum voltage which ensures stable suspension of relatively small quantities of metal U_{\min} is therefore somewhat higher than the first critical U_{1c} .

Boundary of stable suspension of liquid metal in the upper position. The metal is stably suspended with voltage on the inductor higher than the minimum. However, with a further increase in voltage, the metal is elevated, and the moment occurs when it again loses stability, adhering to the inductor copper. We will call this voltage the second critical voltage, and will designate it as U_{2c} . Experience has shown that the boundary for stable suspension of the metal in the upper position, in the same way as the lower, does not depend on the capillary constant of the metal, but in contrast to the lower position, does depend on its volume.

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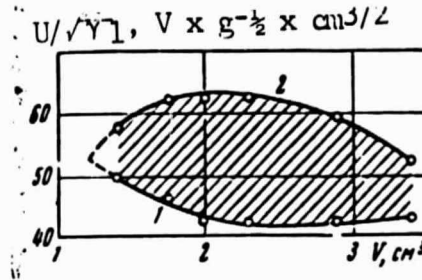


Figure 3. Possible Values for Ratio $U/\sqrt{\gamma_1}$ for Different Volume of Liquid Metal. Curve 1 corresponds to the minimum voltage $U_{\min} \geq U_{lc}$; curve 2 corresponds to the maximum $U_{2c} = U_{\max}$.

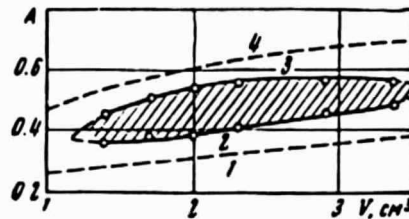


Figure 4. Possible Values for the Coefficient A in the Area of Stable Suspension of Metal of Different Volume in the "Boat" Inductor. Curves 1 and 4 delimit the area of stable suspension of the solid metal; curves 2 and 3 delimit the liquid.

Area of stable suspension of liquid metal. There are thus maximum values for the ratio $U/\sqrt{\gamma_1}$, what is the same, there exists an area of metal position in the inductor depending on the metal volume, in which the metal is stably suspended (fig. 3).

It is apparent from figure 3 that the most applicable volume of molten metal for the examined inductor is in limits of 1.5 - 3.4 cm³.



Figure 5. Limiting Values for the Ratio R/A , Proportional to the Temperature for Different Volumes of Metal. Curves 1 and 4 are for solid metal, curves 2 and 3 for liquid.

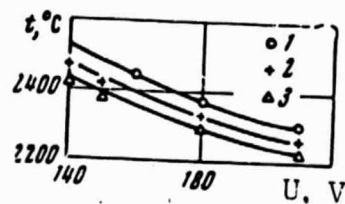


Figure 6. Dependence of Steady-State Temperature of Niobium on Voltage on Inductor.

Key:

Field frequency 440 kHz

1. Weight 16 g

2. Weight 12 g

3. Weight 8 g

Metal temperature change range. Publication [1] has indicated that one can compute the steady-state temperature of the metal that is produced in the given inductor by using formula (1), if one knows the change range for coefficient A . It only depends on the configuration of the field at the metal surface, i.e., is governed by the design of the inductor, the position of the metal in the inductor, and the shape of the metal. Figure 4 presents the dependence of the values of coefficient A on the volume of solid and liquid metal that we obtained experimentally. It is apparent that the range of temperature change for the liquid metal is higher than the solid. However, the value of the

temperature depends not only on coefficient A. We will rewrite formula (1) in the form

$$P_s = \frac{2F}{AS} \sqrt{\frac{\pi p}{\mu_0}} = 0.55 K_T \sqrt{\frac{\pi p}{\mu_0} \frac{R}{A}} \quad (5)$$

where K--coefficient which is equal to the ratio of the actual drop surface to the surface of a sphere of the same volume; R--radius of the sphere with volume V. /220

One can consider the coefficient K to be a constant magnitude, equal to 1.2 for the given inductor, in the first approximation. Consequently, the quantity P_s , on which the steady-state temperature depends, is defined by the R/A ratio. The dependence of the magnitude of R/A on the volume corresponds to an analogous dependence of the metal. Figure 5 shows the limiting R/A values, depending on the volume of metal which are proportional to the temperature. It is apparent from figure 5 that the magnitude R/A, and consequently, the steady-state temperature have a weak dependence on the volume both for liquid, and especially for a solid metal. /221

The boat inductor is thus characterized by a weak dependence of the limiting, i.e., the maximum and minimum, metal temperatures on volume. With the given volume of the metal, its temperature depends on the voltage on the inductor. As is apparent from the graph in fig. 6, the metal temperature drops with a rise in voltage on the inductor.

One should bear in mind that when switching from one model of inductor to another, the critical values of the voltage applied to the inductor, and the metal steady-state temperature can change somewhat because of inaccurate fabrication of the inductor, or as a result of its deformation during operation.¹

One can use the work done as the basis for computing the steady-state temperature and permissible quantities of metal that

¹This partially explains a certain discrepancy in the cited data for the A coefficient with those published in [1,2]. Another source of error [omitted in original text].

POSSIBLE STEADY-STATE TEMPERATURES OF METALS IN
"LOAT" INDUCTOR WHEN HEATED IN VACUUM AND PERMISSIBLE
METAL WEIGHT

Metal	$t_{me}, ^\circ C$	F_{min}, g	F_{max}, g	f, kHz	$t_{min}, ^\circ C$	$t_{max}, ^\circ C$
Al	659	3.0	8.4	440 220 70	1500 1400 1200	1600 1500 1300
Ag	960	11.6	33.0	440 220 70	2050 1900 1650	2200 2000 1800
Cu	1083	9.6	27.0			
Ni	1452	9.4	26.6	440	2150	2400
Co	1500	9.5	27.0	220	1950	2200
Fe	1535	8.6	24.2	70	1600	1800
Ti	1680	5.0	14.1	440 220 70	2000 1800 1600	2200 2000 1750
Zr	1860	7.0	20.0	440 220 70	2300 2100 1650	2500 2300 1950
Rh	1960	13.3	38.0	440	2450	2650
Ru	2282	13.0	37.0	220 70	2300 2050	2500 2200
Hf	2330	14.4	41.0	440 220	2850 2700	3100 2850
Nb	2420	9.4	26.6	440 220 70	2450 2100 1800	2650 2400 2150
Mo	2620	11.2	32.0	440 220 70	2350 2150 1880	2700 2550 2200
Ta	2996	18.0	50.0	440 220	2700 2350	3000 2850
Ir	2454	24.0	68.0	440	2900	3000
Os	3045			220	2600	2800
Re	3164	22.4	64.0	440	2800	3200
W	3410	21.0	60.0	220	2500	2800

can be held by the electromagnetic field in the suspended state in this inductor. The calculation results for field frequencies 440, 220 and 70 kHz are presented in the table. The minimum and maximum weight for the given metal was determined for the volumes

$V_{\min} = 1.5 \text{ cm}^3$ and $V_{\max} = 3.4 \text{ cm}^3$. The steady-state temperature was defined by the technique described in publication [1]. As experience has shown, the obtained temperatures differ by no more than 5% from those presented in the table.

It follows from the table that a number of metals can be melted and poured into the ingot mold in the boat inductor. In this case, the steady-state temperature after melting will be higher than the melting point for metals Al, Ag, Cu, Ni, Co, Fe, Hf, Rh and Ir at frequencies which guarantee their maintenance in a suspended state. The steady-state temperature for Ti, Zr, Nb, Mo and Ru metals can be lower or higher than the melting point, depending on the frequency of the field and the voltage on the inductor. The steady-state temperature for Os, Re, Ta and W metals in the examined frequency ranges will be below the melting point.

CONCLUSIONS

1. Study of the "boat" inductor characteristics indicated that for metals which can be held in the suspended state by the field of this inductor, the limiting, i.e., maximum and minimum, temperatures do not depend on the volume of metal, which promotes conducting experiments that are associated with metal evaporation.
2. Increase in the voltage applied to the inductor is accompanied by a decrease in metal temperature.
3. Outflow of the metal from the inductor is associated with a definite critical height of metal suspension, and does not depend on its volume and physical properties.
4. In addition to producing castings, the inductor can be used to crystallize metals in the suspended state. Ti and Zr can be crystallized in a vacuum at field frequency 70 kHz, Nb and Mo at frequency 440 kHz, while Fe, Ni and Co in a helium atmosphere at frequency 70 kHz.

5. By using additional heating of the metal by an electron beam, one can melt Ru, Nb and Mo at a frequency of 70 kHz, and Mo, Ta, Os, Re, and W at frequency 220 and 440 kHz.

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